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## Mixed Source Interrogation of Steel Shielded Special Nuclear Material Using an Intense Pulsed Source

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### Abstract

This paper explores the benefits of using a mixed photon and neutron radiation source for active detection of special nuclear material. More than fifty irradiations were performed using an 8 MV electron accelerator employing an induction voltage adder (IVA). The experiments used a high atomic number converter to produce a Bremsstrahlung photon spectrum which was then used to create a neutron source via a nuclear interaction with heavy water (deuterium oxide, D<sub>2</sub>O). This mixed particle source was used to irradiate a depleted uranium (DU) sample, inducing fission in the sample. Several thicknesses of steel shielding were tested in order to compare the performance of the mixed photon and neutron source to a Bremsstrahlung-only source. An array of detectors were fielded to record both photons and neutrons emitted by the fission reactions. A correlation between steel shielding and a detection figure-of-merit can be seen in all cases where the Bremsstrahlung-only source was used. The same relationship for the mixed photon-neutron source is less consistent. The data collected from the fielded detectors is compared to MCNP6 calculations and good agreement is found.

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**Keywords:** Active detection; photofission; neutron induced fission; IVA; uranium

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### 1. Introduction

Photons with energies higher than ~5 MeV, and neutrons of any energy, can induce fission in special nuclear materials and, in turn, the products can be detected and identify the material as fissile or fissionable. The

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experiments discussed here used a high atomic number converter to produce an 8-MeV endpoint energy Bremsstrahlung photon spectrum which was then used to irradiate a D<sub>2</sub>O insert which produces a 2-3 MeV endpoint neutron spectrum for a small measurable loss in photon fluence. This mixed interrogation source is potentially favourable for non-hydrogenous shielding configurations which are highly attenuating to photon beams. However, neutrons add significant complexity both operationally in terms of radiation dose and, also, for analysis in discriminating fission signals due to high backgrounds and activation products. The added performance benefits must outweigh these complications if the neutron component of the source is to be deployed. To assess these effects, a depleted uranium plate was irradiated and induced-fission signatures were measured as a function of the thickness of steel shielding surrounding the target. This was performed with the accelerator operating in normal Bremsstrahlung mode with a D<sub>2</sub>O insert to generate neutrons and with a H<sub>2</sub>O insert to measure the relative photon attenuation of the secondary converter. The non-fission related radiation background produced during an interrogation (the active background) was also measured and characterised. This will support an understanding of the level of complexity the neutron component introduces.

## 2. Experimental Setup

The experiments were performed at the Mercury facility at the Naval Research Laboratory, Washington DC. In total, more than 110 shots were fired investigating several different parameters pertinent to active detection, of which a subset of 52 shots was used for the present analysis. As shown in Table 1, three families of shots were analysed. These relate to the radiation converter target used, i.e., bremsstrahlung, D<sub>2</sub>O and H<sub>2</sub>O. In the case of the Bremsstrahlung source, the converter used was the standard high-Z tantalum diode [2] used in previous active detection campaigns [3]. A deuterated water insert was included in the collimation to produce a fast neutron component via the  $^2\text{H}(\gamma, n)^1\text{H}$  process. As a control measure, the D<sub>2</sub>O insert was replaced with a H<sub>2</sub>O insert for a small number of shots in order to understand the photon attenuation of the heavy water converter. For each of the three converter configurations, a number of stainless steel shielding thicknesses were investigated. Stainless steel was chosen due to its abundance in shipping cargos [4] and because of its high photoneutron threshold and low relative yield in comparison with other high-Z materials such as lead and tungsten. If a low photoneutron threshold material had been used, the additional neutrons produced by the shielding material may contribute to the induced fission and confuse the analysis of these experiments. Table 1 also shows the shielding thicknesses used and their corresponding areal masses. Most configurations were repeated at least once to ensure repeatability in the results.

Table 1. Experimental configurations for the assessment of a photoneutron source

Converter	Target	Shielding Material	Shielding thickness (in)	Shielding areal mass (g/cm <sup>2</sup> )	Number of repeats
Bremsstrahlung only - Tantalum	Depleted Uranium	None	0	0	4
		Steel	2.5	50	4
			4.5	90	6
			7.5	150	4
	None – Active Background	Steel	1.5	30	2
			2.5	50	2
			3.5	70	2
			7.5	150	2
D <sub>2</sub> O	Depleted Uranium	None	0	0	4
		Steel	2.5	50	3
			4.5	90	2
			7.5	150	3
	None – Active Background	None	0	0	2
		Steel	2.5	50	2
			4.5	90	2
H <sub>2</sub> O	Depleted Uranium	None	0	0	2
		Steel	4.5	90	1
	None – Active Background	None	0	0	2
		Steel	4.5	90	1

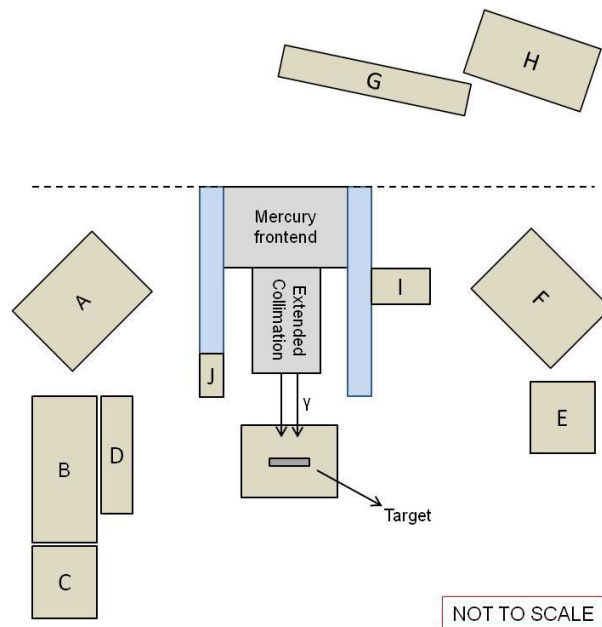


Figure 1. Experimental layout for whole series

The experimental configuration is shown in figure 1. More than 80 individual detectors were fielded in this campaign on 10 stands (labelled A to J), a combination of neutron and gamma detectors with a range of sensitivity

and energy discrimination. A full description of the experimental setup can be found in Woolf et al. (2013) [1]. This paper focuses on the AWE  $^3\text{He}$  stand J as shown in figure 2. This stand was specifically setup to be identical to that in the March 2011 series of experiments [2] in which initial investigations were made into the performance of a bremsstrahlung source with respect to lead and borated polyethylene shielding. This ensures good fidelity when comparing the two sets of experiments and Monte Carlo simulations as previous work has been done to validate this relationship [3].

The  $^3\text{He}$  tubes fielded in this campaign had purpose built fast neutron moderation. This is a combination of 2.54 cm thickness of polyethylene, 1 cm flexi-boron and 0.011 cm cadmium foil. This combination allows reduction of thermal background and is more sensitive to  $\sim 1$  MeV neutrons which is consistent with the expected fission spectrum. A description of how the detectors and moderation have been optimised is described elsewhere [4]. The data from the  $^3\text{He}$  tubes were acquired using a Canberra multiport [5] and the Genie 2000 software tool [6]. The neutrons were counted in 30-ms time bins and the data read using the Naval Research Laboratory in house software. The data were exported to ASCII to allow manipulation in any processing tool of choice. In addition, raw oscilloscope data for the first second of the record were also acquired.

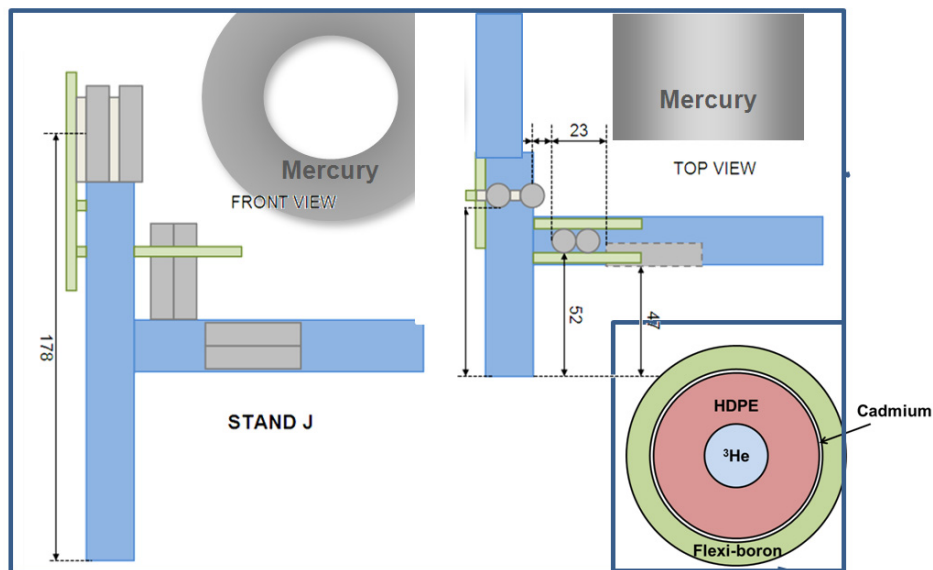


Figure 2. Positions of six  $^3\text{He}$  detectors relative to Mercury rails

### 3. Analysis Method

The data from these experiments were analysed in the same manner as those for the previously presented series [5]. A figure-of-merit (FOM) was used to quantify the confidence in the analysed decision values. All traces from the six detectors were reviewed for anomalous results, as were the initial second scope traces where available. In particular, the scope traces were examined to ensure that the detector dead time, i.e., the time taken for the detector to display normal neutron pulses after the machine fired, was small relative to the acquisition time bin. For the Bremsstrahlung and  $\text{H}_2\text{O}$  converter experiments, the recovery time was within the initial 30 ms time bin. However, the initial fluence of fast neutrons in the  $\text{D}_2\text{O}$  converter experiments caused pulse pileup in the  $^3\text{He}$  tubes and resulted in an unrepresentative value in the first time bin as shown in figure 3. For this reason, this first time bin was omitted for

all shots. This has little effect on the FOM for the Bremsstrahlung-only shots as it is averaged between 5 and 10 seconds to eliminate fluctuations in the background at early times.

Comparison of first 10 time bins with a photon and photoneutron source for 3he6

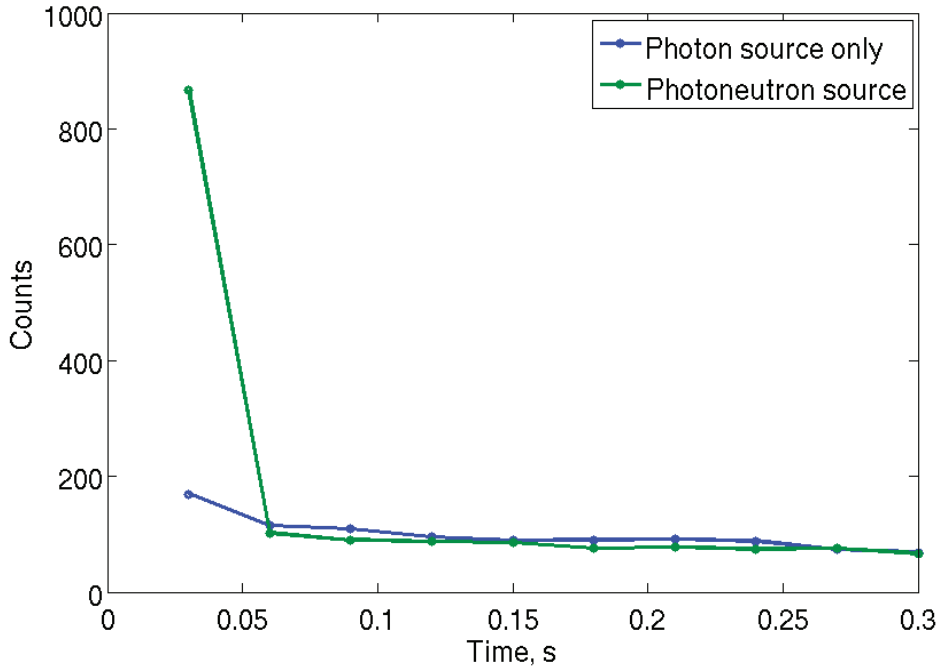


Figure 3. Comparison of early time neutron signal for Bremsstrahlung and D<sub>2</sub>O converter configurations

The figure-of-merit (FOM) used in the present analysis is defined as

$$FOM(t) = \frac{S(t) - \bar{B}(t)}{\sigma_B(t)}$$

Where  $S$  is the neutron signal as a function of time from the shot in question,  $B$  is the mean null background as discussed above, and  $\sigma_B$  is the standard deviation of the cumulative background. The FOM calculation was performed for all shots as a function of time and displayed as cumulative plots. Figure 4 shows an example of such a plot. The blue line shows the cumulative signal acquired from the raw data, the green line is the cumulative null background (average of all non-lead null shots), and the red line is the FOM. The shaded tan area in the figure represents two standard deviations of the background sample above the mean background and the green shaded area signifies five standard deviations. These cumulative plots give the figure-of-merit as a function of time which can help determine the length of time that data must be acquired for a deployed system.

The FOM was then averaged for five of the six detectors and the results for all shielding configurations are shown in figure 5. The sixth detector was omitted due to a noticeable drop in counts relative to the other detectors during the measurements and was assumed to be not functioning correctly. Figure 5 clearly shows the relationship between FOM and areal mass of shielding for the different shot configurations. The error bars on each point are representative of one standard deviation between the results of the five detectors. The figure also shows that there is a reduction in the amount of detectable fission neutrons when a water converter is placed in the collimator, which is likely to be caused by the attenuation of the Bremsstrahlung source. In addition, there is a recovery of this reduction when the water canister is filled with deuterated water. One theory for this recovery is that the production

of fast neutrons in the secondary converter can stimulate fission in the DU sample. The cross section for  $^{235}\text{U}$  is much higher at lower neutron energies and as the  $\text{D}_2\text{O}$  converter produces a broad neutron spectrum, this implies a higher quantity of  $^{235}\text{U}$  component may provide a larger signal.

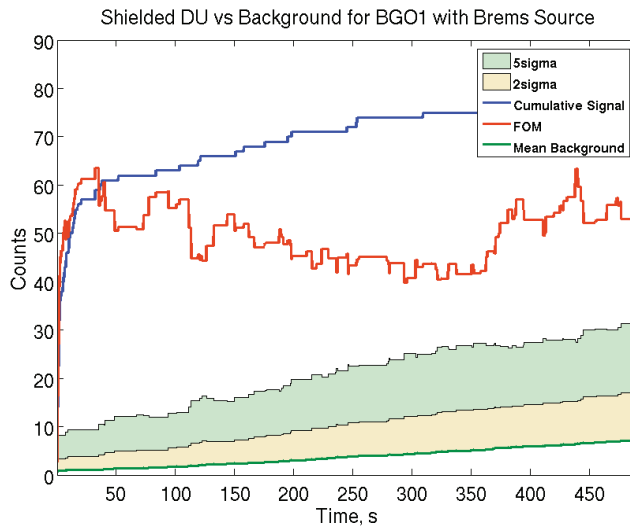


Figure 4. Figure-of-merit (FOM) relationship to signal and background for a stainless steel shielded DU shot.

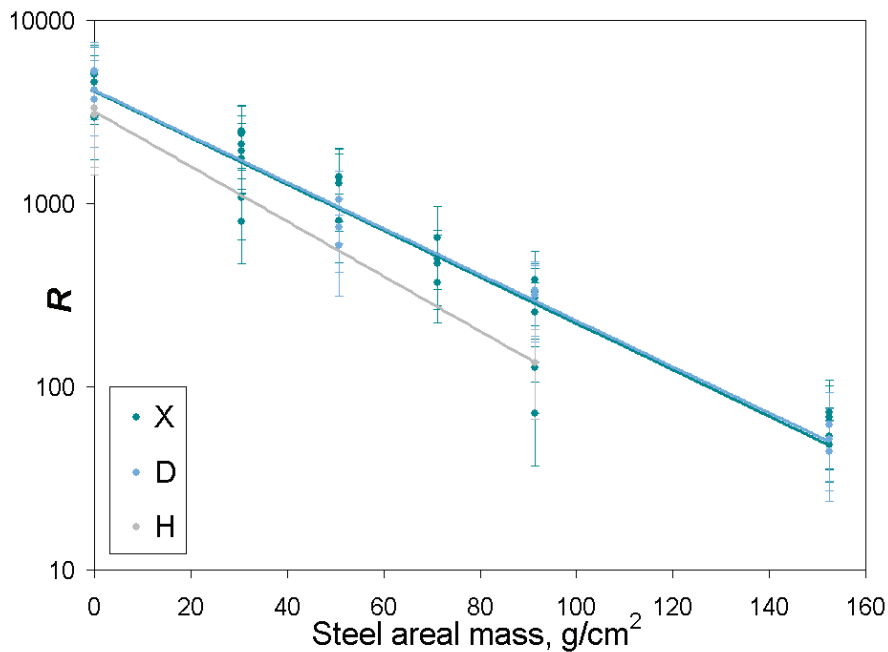


Figure 5. Figure-of-merit averaged over five  $^3\text{He}$  tubes.

#### 4. Comparison to Monte Carlo calculations

Monte Carlo simulations of the experimental setup were performed for comparison with the measured values. Proton recoils from neutron interactions in the  $^3\text{He}$  tubes were tallied in MCNP6 and a comparison of the cumulative signal with respect to time for the bare DU plate is shown in figure 6. Both the bremsstrahlung only (X) and the photoneutron source (D) are plotted.

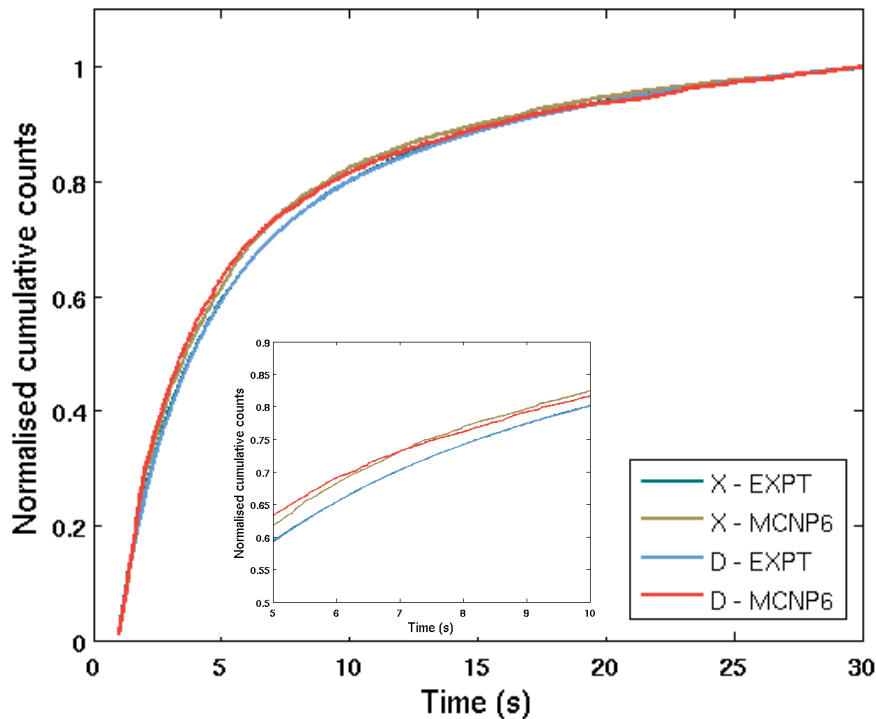


Figure 6. Normalised cumulative counts with respect to time for a Bare DU target. Inset – increased detail view.

The counts were normalised to allow comparison of the neutron rate. The MCNP6 calculations can be seen to over predict the neutron rate by a small percentage in the 5-10 second post-shot region. This can be seen in more detail in the inset of Figure 6. The same relationship can be seen for three different steel shielding configurations shown in Figures 7-9 although it is clear that the MCNP6 calculations were suffering from poor counting statistics in the thickest shielding configuration, as were the experimental data to a lesser degree.

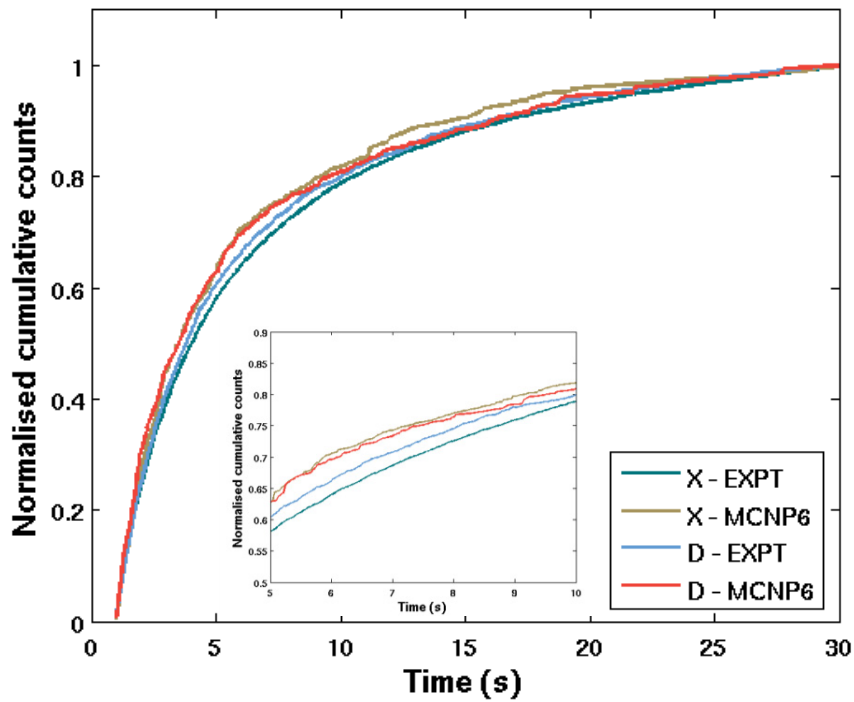


Figure 7. Normalised cumulative counts with respect to time for a DU target with 2.5'' steel shielding.

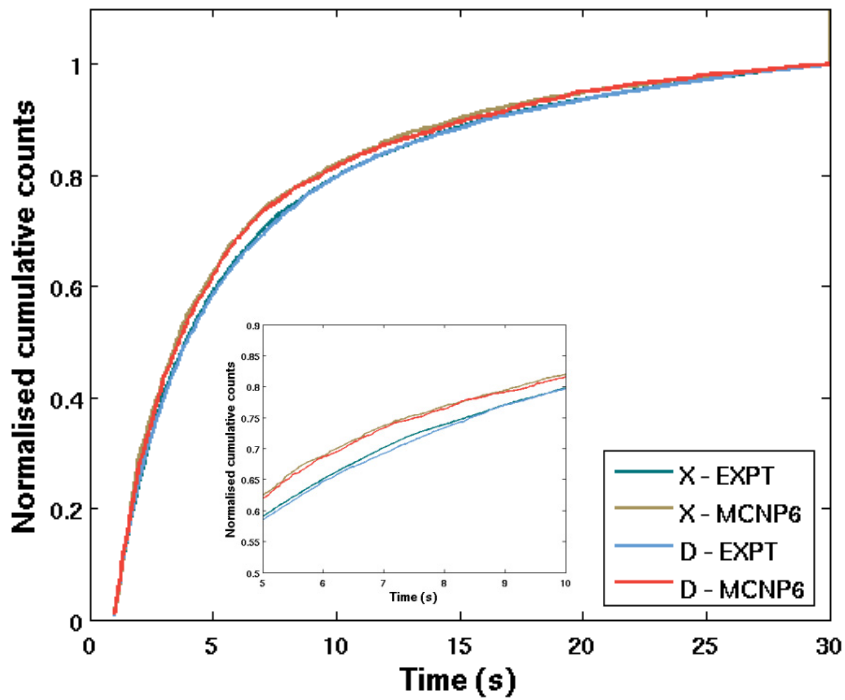


Figure 8. Normalised cumulative counts with respect to time for a DU target with 4.5'' steel shielding.



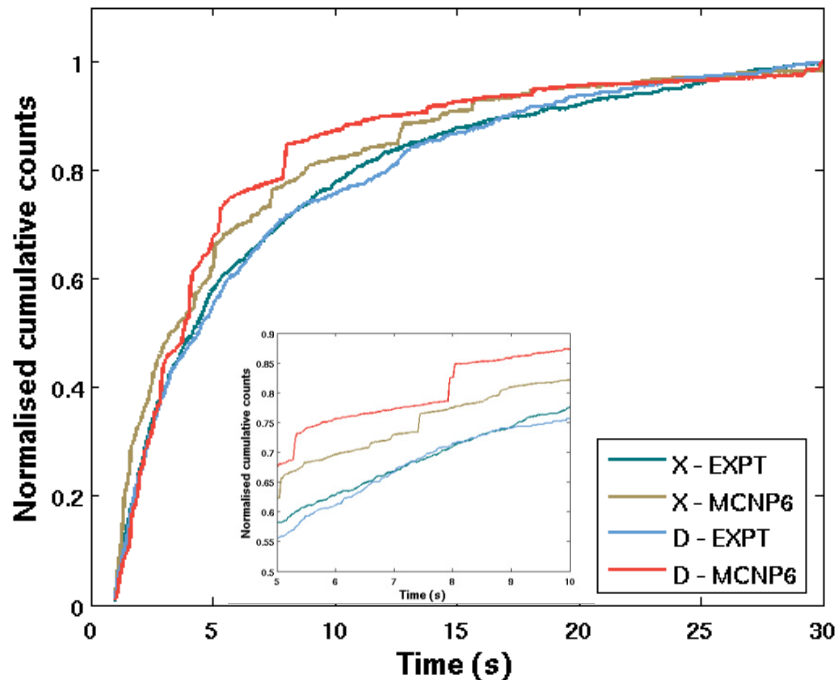


Figure 9. Normalised cumulative counts with respect to time for a DU target with 7.5'' steel shielding.

It is worthwhile to compare the gradient of the FOM from the experimental data to the number of fissions in the DU target as calculated in MCNP6. Without folding in the response of the  $^3\text{He}$  diagnostic with respect to energy, a simple assumption is that the relationship between the number of fissions induced in the target plate and FOM is linear when the relative backgrounds are low. This assumption will be tested in calculations at a later date. A comparison of the gradients for both the Bremsstrahlung only case (X) and the  $\text{D}_2\text{O}$  experimental series (D) with their respective MCNP6 calculations are shown in Figure 10. It can be seen that the gradient of the areal mass – FOM relationship compares well with that of the induced fissions. The points where the lines intersect are not meaningful due to the relative errors in both the calculations and the experimental spread of the data.

## 5. Discussion

This paper analysed the results of  $^3\text{He}$  tubes fielded in experiments with a combined photon-neutron source to assess its performance for active interrogation of special nuclear material. The set of  $^3\text{He}$  tubes were used to record the returning fast ( $\sim 1\text{MeV}$ ) neutron signal from induced fission events. A figure-of-merit was used to estimate the performance of this detector for a variety of shielding thicknesses and three source production configurations. When plotted as a function of shielding areal mass, the FOM magnitude is reduced when the  $\text{H}_2\text{O}$  convertor target is in place. This is due to the attenuation of the source as it passes through the water canister. When the water is replaced with deuterated water, and consequently a source of neutrons is produced, the FOM magnitude increases to a level similar to that of convertor target present. This indicates that using an interrogation source with a neutron component for shielding with high photon attenuation could add a benefit given the correct source ratio. Further calculations for a system of interest, used in conjunction with knowledge of typical cargo contents will provide an estimation of the level of performance increase that might be expected from using a mixed photon-neutron source.

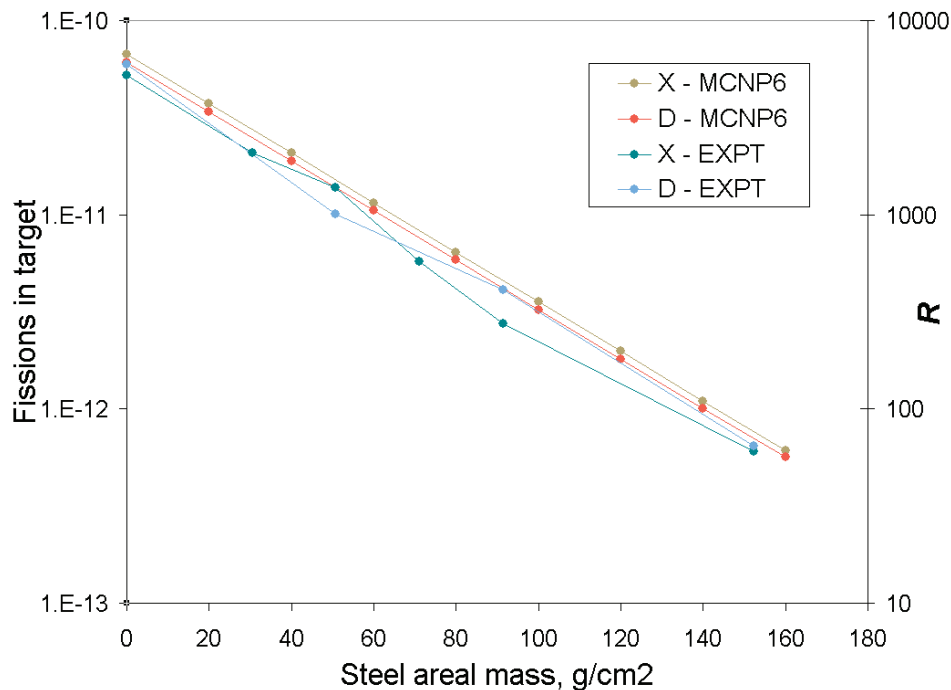


Figure 10. Comparison of calculated number of fissions with experimental R for photon only and photoneutron sources

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